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Study of Massive Timber Walls based on NLT and Post Laminated LVL

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EXECUTIVE SUMMARY

Currently the massive timber shear walls are mainly made from Cross Laminated Timber (CLT), which possesses a high in-plane shear strength and rigidity. But only part of its elements (mainly the vertically aligned laminae) are engaged in carrying the vertical load and that could be a limitation when designing taller timber structures or wherever higher vertical load is present. This project studied alternative solutions to massive timber shear wall system, based on Nailed Laminated Timber (NLT) and post laminated LVL (Laminated Veneer Lumber).

The test was conducted on three levels: shear test on glue/nail line, bending-shear test on a small element, and full size wall test under lateral loading. The former two tests investigated the properties of basic elements in NLT and post laminated LVL. The results were used to design and predict the performance of full size shear walls.

The NLT walls were tested under two conditions: without sheathing and with plywood sheathing. The wall without sheathing had the lowest load-carrying capacity and lowest stiffness. Adding plywood sheathing significantly increased its strength and stiffness. The failure in the wall with sheathing was at the sheathing connections, in the forms of nail withdrawal, nail head pull through, and nail breakage. The NLT wall with sheathing had a peak load up to 60% higher than the comparable light wood frame wall, also with a higher stiffness and better ductility. NLT shear walls have an internal energy dissipating capacity which CLT and post laminated LVL walls lack.

The post laminated LVL walls behaved as a rigid plate under lateral loading, with little internal deformation. The failure occurred at the holdowns not within the wall. The size effect of its shear strength was studied and an equation was developed to calculate the shear strength of a large size wall plate.

Both products have efficient vertical load bearing mechanism by arranging all elements in the vertical direction. They may serve as alternative to light wood frame walls or CLT walls. Some guidelines for the application and design of NLT shear walls and post laminated LVL shear walls were proposed.

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1 INTRODUCTION

Massive timber technology has been widely used in modern timber construction. The shear wall system in massive timber construction is typically made from Cross Laminated Timber (CLT). Due to the orthotropic properties of CLT, the in-plane shear strength and rigidity of the panel tends to be very high, but only the longitudinal plies aligned vertically are mostly engaged to carry the vertical load. One can argue that this might not be the most efficient way to handle vertical loads in walls especially for tall timber buildings.

There are alternative massive timber concepts that can be used for shear wall applications, such as post laminated LVL (Laminated Veneer Lumber), Nailed Laminated Timber (NLT), Dowel Laminated Timber, post laminated GLT (Glue-Laminated Timber), and LVL panels. Currently there is little technical information available for designers if they want to consider using these systems as shear walls. This project studied the feasibility and performance of massive timber walls based on Nail Laminated Timber (NLT) and post laminated LVL, in order to identify the potential as well as limitation of these systems. Both products bear the vertical load more efficiently by aligning all the wood elements in the vertical direction.

2 MATERIAL AND METHODS

The test was conducted on three levels: shear test on glue/nail line, bending-shear test on a small element, and full size wall test under lateral loading. The material used in the manufacturing and testing of the products is shown in Table 1.

Table 1 Material list

Test	Item	Material
NLT test	Lumber	Kiln dried SPF No. 1 & Better 2 by 4 (38 mm by 89 mm)
	Nail for connection and bending-shear test	28° wire weld nails with smooth shank, nominal length 89 mm (3.5 in), nominal diameter 3.3 mm (0.13 in), head offset
	Nail for NLT wall test	28° wire weld nails with smooth shank, nominal length 76 mm (3.0 in), nominal diameter 3.0 mm (0.12 in) , head offset
	Plywood panel	12.6 mm (0.5 in) thick, Canadian spruce
	Nail for plywood	28° wire weld framing nails, nominal length 50 mm (2 in), nominal diameter 2.9 mm (0.113 in), head offset
	Holdowns	Simpson Strong-Tie HTT5
	Angle brackets	Simpson Strong-Tie AE116-R
Post laminated LVL test	Post laminated LVL	Brisco Fine Line™ Panels, 83 mm (3.25 in) thick
	Holdowns	Simpson Strong-Tie HTT5
	Angle brackets	Simpson Strong-Tie AE116-R
	Nails for holdowns and angle brackets	76 mm (3 in) common nail, 3.76 mm (0.148 in) in diameter

2.1 Nail Laminated Timber

The test configurations for NLT are shown in Table 2. The dimensions and nailing patterns of the specimens can be found in Appendix A. All nails used were driven in by a pneumatic nail gun.

Table 2 Experimental design for NLT tests

Type of test	Replicates	Configurations	Specimens
Nail connection test	15	Nails parallel to wood grain	H-Block test
	15	Nails perpendicular to wood grain	H-Block test
Bending-shear test	10	Without sheathing	Depth 152 mm, span 762 mm
	10	Plywood sheathing on one side	Depth 152 mm, span 762 mm
Full size wall test	1	Without sheathing	Width 2.32 m, height 2.34 m
	2	Plywood sheathing on one side	Width 2.32 m, height 2.34 m

2.1.1 Nail connection test

The nail connection test investigated the performance of a single nail under shear when driven through two layers of lumber. Two sets of specimens were tested: one set with the nails parallel to the wood grain, and the other set with nails perpendicular to the wood grain, as shown in Figure 1. Since the nail was longer than two times the lumber thickness, there were two nails present on each shear plane. The load was applied on the center member with a rate of 2.54 mm/min. Two transducers were installed to measure the relative displacement between the main member and side members. The test setup is shown in Figure 2. Moisture blocks were cut from tested specimens to measure the moisture content and specific gravity. The moisture content was calculated in accordance with ASTM D4442-16. The specific gravity was calculated in accordance with Test Method A of ASTM D2395-17, based on oven dried weight and volume at testing.

2.1.2 NLT bending-shear test

Four layers of lumber were nailed together to form the specimen for bending-shear test. For one set of specimens, plywood sheathing was attached to one side, in order to evaluate the effect of sheathing on the NLT performance. The two types of specimens are shown in Figure 3. The specimen was loaded at the center with a span/depth ratio of 5:1. The test was conducted in accordance with the Flexure Test in ASTM D198-15. The deflection of the midspan relative to the supports on the neutral axis was measured by a Linear Voltage Displacement Transducer (LVDT) with a yoke. The bending-shear test setup is shown in Figure 4.

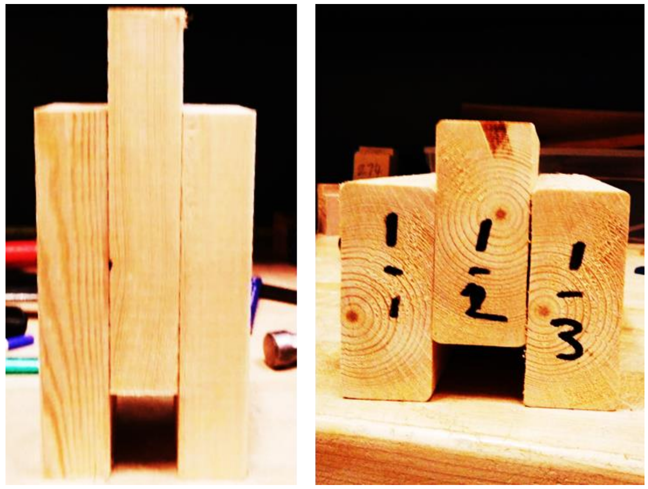

Figure 1 Specimens for nail connection test

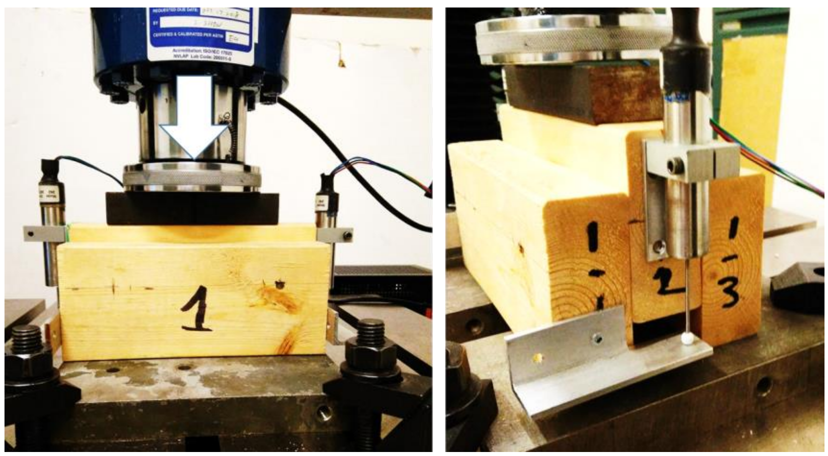

Figure 2 Test setup for nail connection test

Figure 3 Specimens for NLT bending-shear test

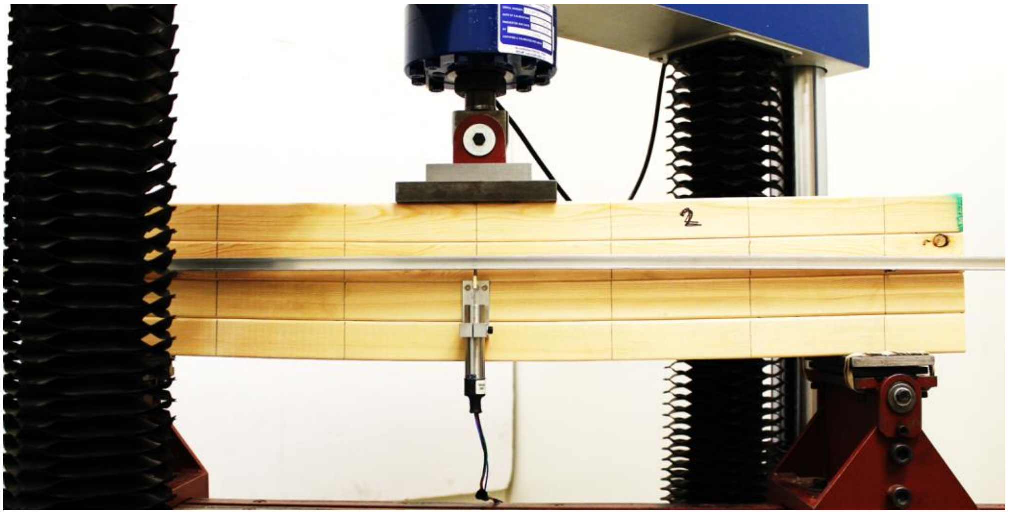

Figure 4 Test setup for NLT Bending shear

2.1.3 Full size NLT wall test

The NLT wall was made by nailing 61 pieces of 2 by 4 lumber together, following the pattern shown in Figures A-8 and A-9 in Appendix A. The width and the height of the wall were 2.32 m and 2.34 m, respectively. Three specimens were manufactured: one without sheathing, and two with plywood sheathing. For the sheathing, two plywood panels were oriented horizontally, with a gap of 6 mm (0.25 in) in between. The nails were placed at the perimeter of the panel, as well as along the lumber length every 457 mm (18 in). The nail spacing was 150 mm (6 in) at the perimeter and 300 mm (12 in) in other places. The pattern and spacing were similar to that used in a typical light wood frame shear wall. The nail edge spacing was 19 mm (0.75 in). The wall specimen during manufacturing is shown in Figure 5.

The tests were conducted on MTS Flextest System in accordance with ASTM E564-06 (2012) and ASTM E2126-11. The test setup is shown in Figure 6. Holdowns were installed at the four corners, and the angle brackets were installed on one side of the wall. Four transducers were mounted to measure the wall displacement at different locations. The monotonic loading had a loading rate of 10 mm/min. The cyclic loading used CUREE basic loading protocol, as found in Method C of Section 8.5 in ASTM E2126-11. Its loading history and detailed amplitudes for each cycle/step could be found in Appendix B. The loading rate for cyclic test was 1 mm/s.

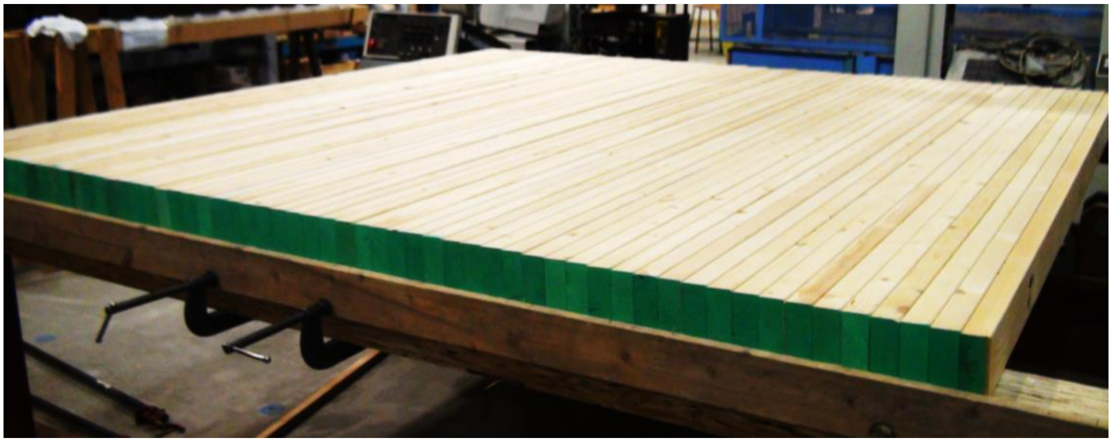

Figure 5 NLT wall specimen during manufacturing

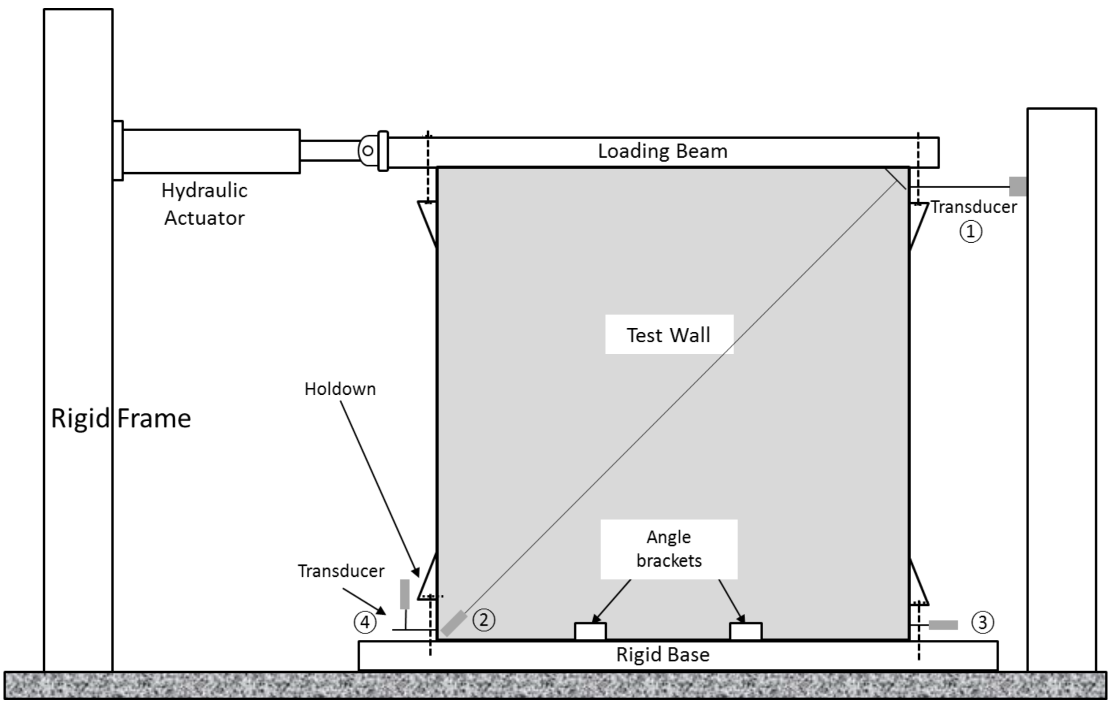

Figure 6 NLT wall test setup

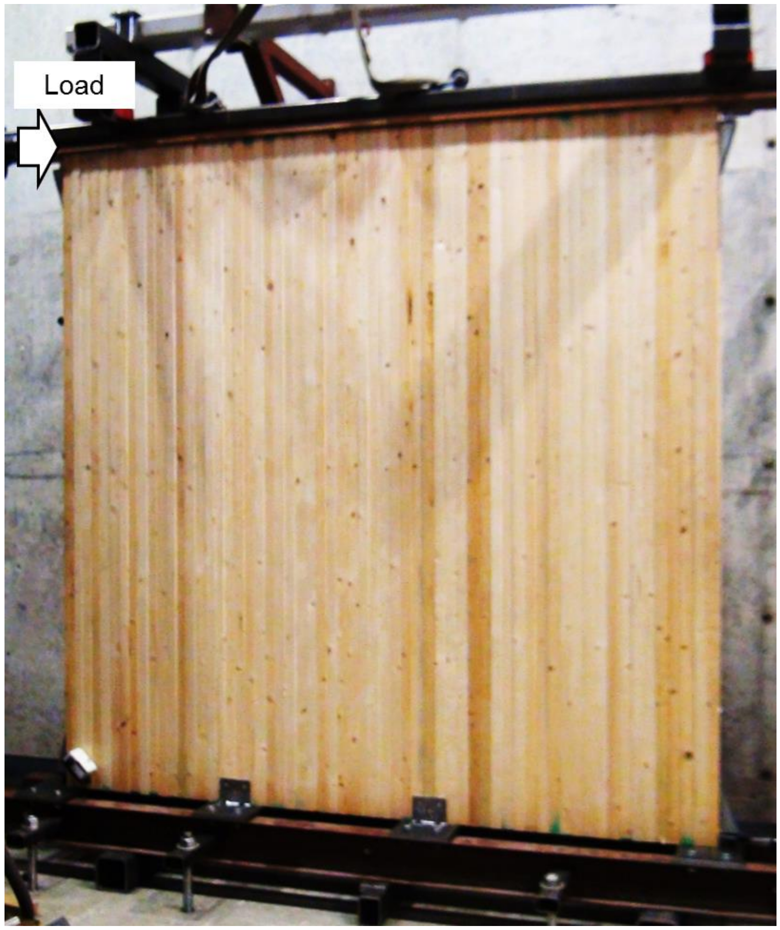

Figure 7 Test assembly for NLT wall tests

2.2 Post Laminated LVL

The test configurations for post laminated LVL are shown in Table 3.

Table 3 Experimental design for post laminated LVL tests

Type of test	Replicates	Configurations	Specimens
Glueline shear test	28	ASTM D143-14	Block shear test
Bending-shear test	30	Depth/span ratio 5:1	Depth 76 mm, length 456 mm
Full size wall test	2	Holdowns at four corners	Width 1.27 m, height 2.44 m

2.2.1 Block shear test and bending shear test

The block shear test was conducted in accordance with Section 14 of ASTM D143-14, with a loading speed of 0.6 mm/min. The test setup is shown in Figure 8.

The bending shear test was conducted in accordance with the Flexure Test in ASTM D198-15. The span/depth ratio was set at 5:1 in order to create shear failure. The specimen was loaded at the center with a loading rate of 1.4 mm/min. The deflection of the midspan relative to the supports on the neutral axis was measured by a Linear Voltage Displacement Transducer (LVDT) with a yoke. The nominal dimension of the specimen was 80 mm by 75 mm by 456 mm (width by depth by length). The span was 381 mm. The test setup is shown in Figure 9. Moisture blocks were cut from tested specimens to measure the moisture content and specific gravity. The moisture content was calculated in accordance with ASTM D4442-16. The specific gravity was calculated in accordance with Test Method A of ASTM D2395-17, based on oven dried weight and volume at testing.

Figure 8 Block shear test setup

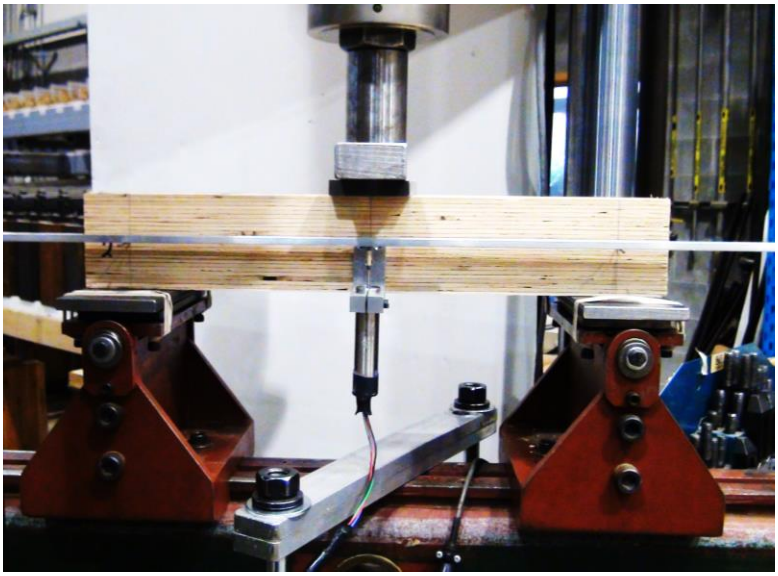

Figure 9 Post laminated LVL bending-shear test setup

2.2.2 Full size post laminated LVL wall test

The post laminated LVL shear walls had a width of 1.27 m (50 in) and a height of 2.44 m (96 in). The test configuration was similar to that shown in Figure 6, only with a different size. One angle bracket was installed on one side of the wall due to its limited width. The test assembly is shown in Figure 10. Two replicates were tested under monotonic loading. The loading rate was 10 mm/min.

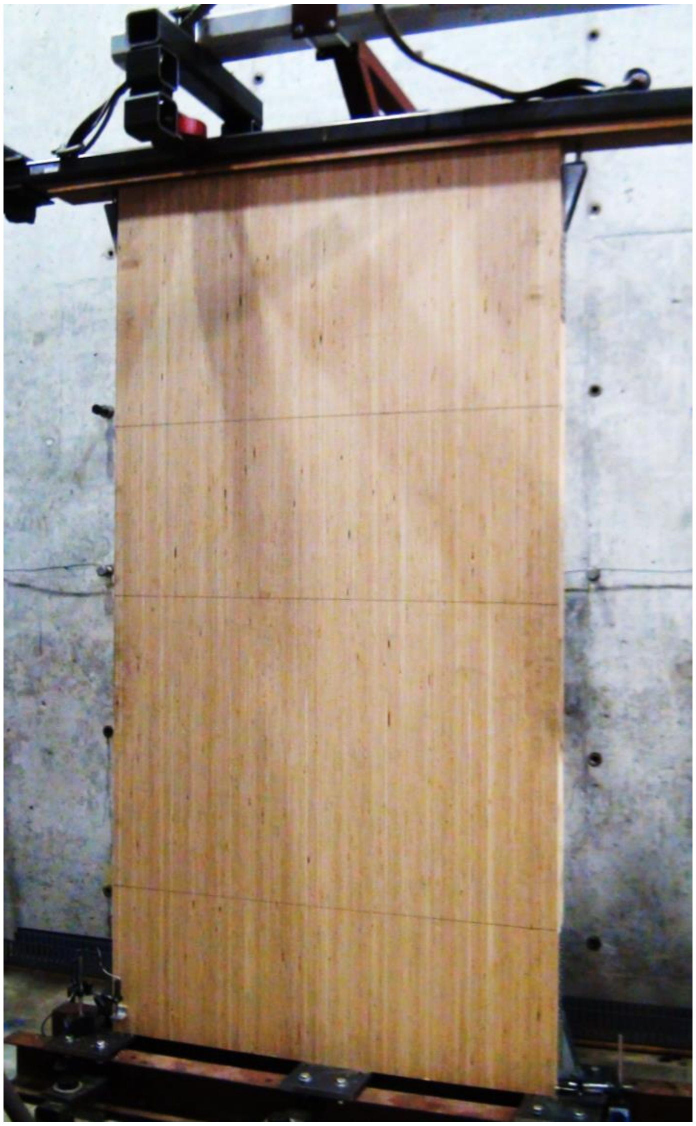

Figure 10 Post laminated LVL shear wall test setup

3 RESULTS AND DISCUSSIONS

3.1 Nail Laminated Timber

The average moisture content of the lumber used in the NLT test was 12.2% (CV 3%), and the average specific gravity was 0.446 (CV 9%).

3.1.1 Nail connection test

The nail connection test results are shown in Table 4. The load-displacement relationship of every specimen is plotted in Figure 12. The specimens with nails perpendicular to grain had a higher average peak load, and also a higher displacement at peak load. Due to the high variation of stiffness results, the difference of stiffness between the two groups was not statistically significant. The nails were bent under lateral load, and at the same time were pulled out from the wood, as shown in Figure 11. The bending of the nails also compressed the wood to make the nail pulling out increasingly easier.

Table 4 Summary statistics of nail connection test

	Peak load (N)		Displacement at peak load (mm)		Stiffness (N/mm) 500-2000N		Stiffness (N/mm) 500-4000N	
	Para	Perp	Para	Perp	Para	Perp	Para	Perp
Maximum	5855	7218	14.6	20.6	20920	11678	1867	2677
Minimum	4064	4933	6.3	10.3	2217	3098	540	744
Average	4982	5958	10.0	13.2	7273	6089	1088	1420
Stdev	498	652	2.7	2.7	4849	2411	392	723
CV	10%	11%	27%	20%	67%	40%	36%	51%
Difference	20%		32%		-16%		31%	

Note: difference was calculated by *(average of Perp / average of Para)-1*; Para: nails parallel to grain; Perp: nails perpendicular to grain

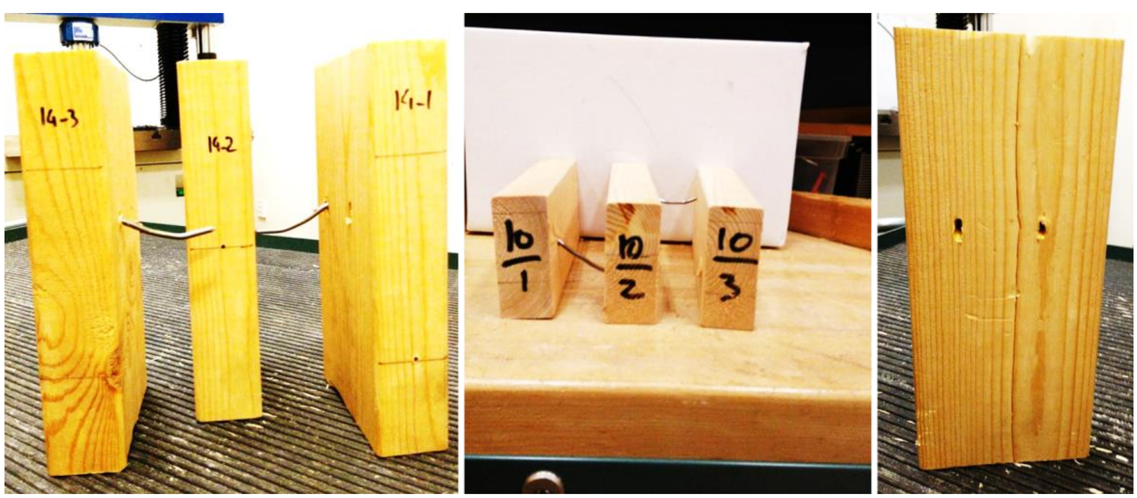

Figure 11 Failure mode in nail connection test

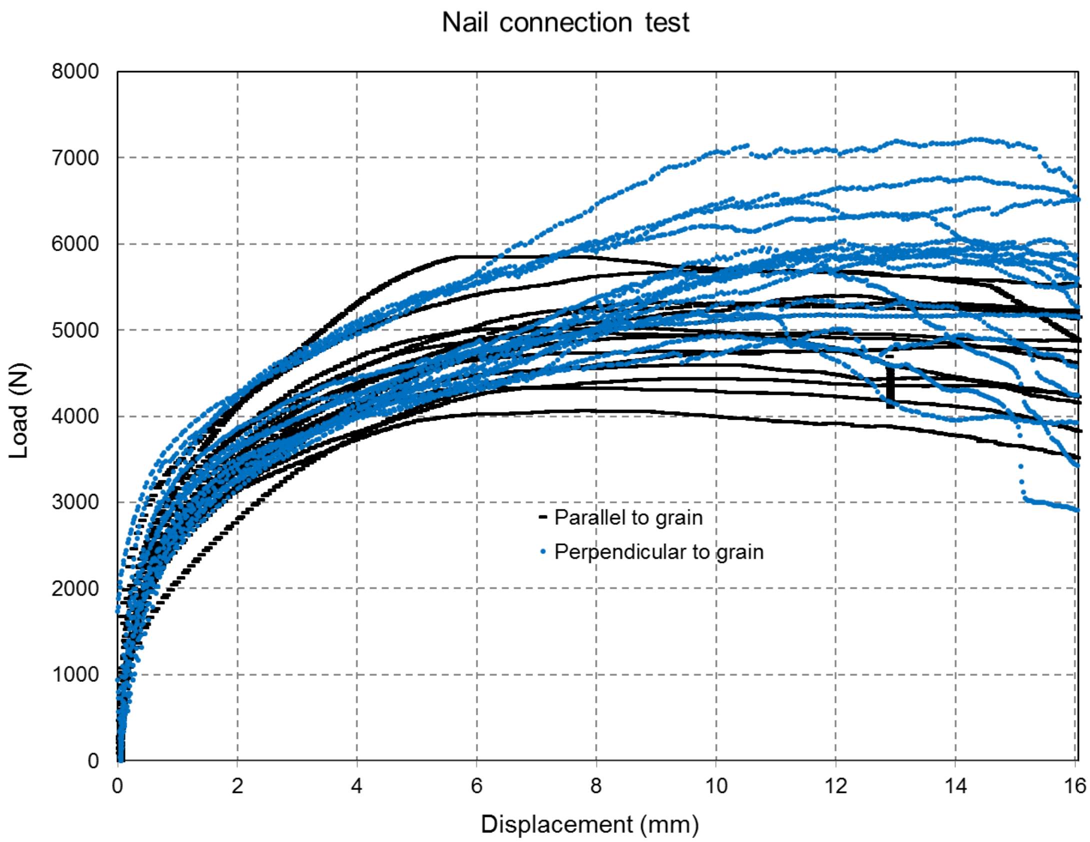

Figure 12 Load-displacement relationship of specimens in nail connection test

3.1.2 Bending shear test

The NLT bending-shear test results are shown in Table 5. The difference of the average peak load in the two groups was 5%, and the difference was not statistically significant. The group with plywood sheathing had a significantly higher stiffness than the group without sheathing, 54% higher on average.

Table 5 Summary of NLT bending shear test results

	Peak load (N)		Displacement at peak load (mm)		Stiffness (N/mm) 500-2000N	
Sheathing	No	Yes	No	Yes	No	Yes
Maximum	42982	41167	21.5	20.8	2776	6075
Minimum	30383	21784	14.5	5.7	2380	2835
Average	37268	35378	18.0	15.3	2532	3899
Stdev	4041	5890	2.5	5.3	124	868
CV	11%	17%	14%	34%	5%	22%
Difference	-5%		-15%		54%	

Note: difference was the group with sheathing compared to the group without sheathing

The load displacement curves of three specimens with the highest peak loads in each group were plotted in Figure 13. For the specimens with sheathing, the load dropped several times before eventually reaching the peak load, as a result of the plywood fracture under tension. Both groups had brittle failure mode caused by the failure of lumber/plywood on the tension side, as shown in Figure 14. The nails were deformed under shear, as indicated by the relative movement between adjacent lumber elements. But that deformation was generally recovered after the load was released. No significant nail deformation was found after taking the tested specimens apart. The plywood failure mode indicates that this bending test configuration is not appropriate for getting the load slip behavior of the nail connection in NLT. The results showed that adding plywood sheathing would significantly increase the stiffness of the NLT.

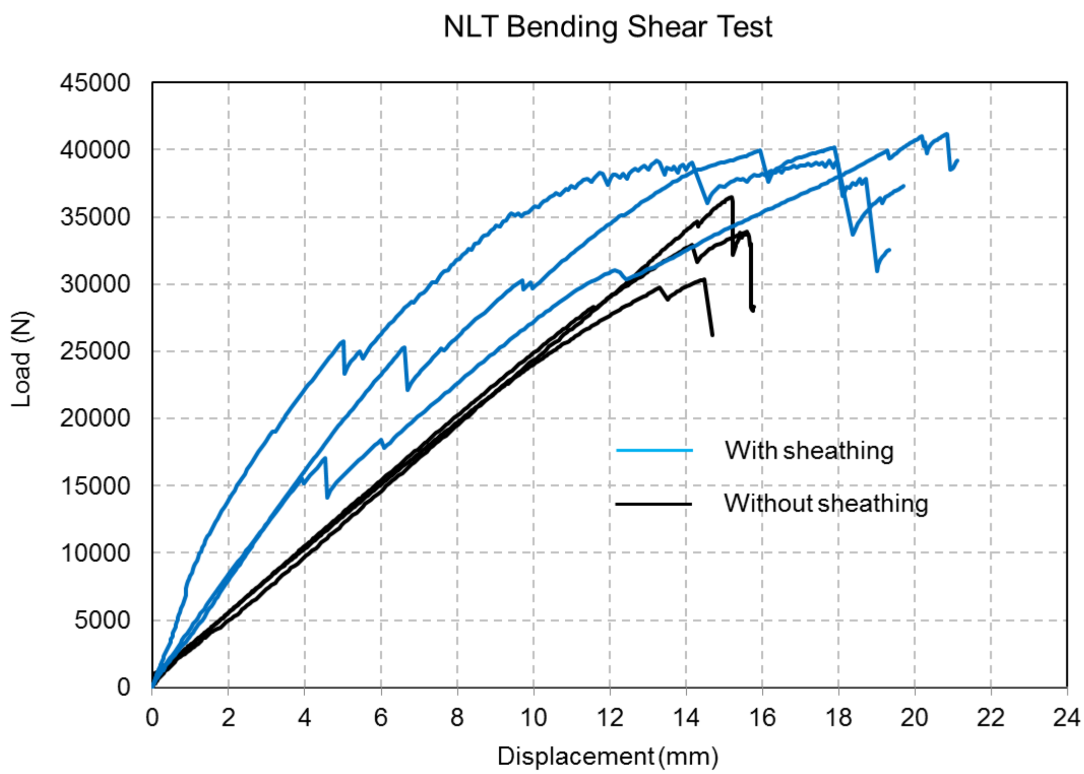

Figure 13 Load-displacement relationship in NLT bending shear test

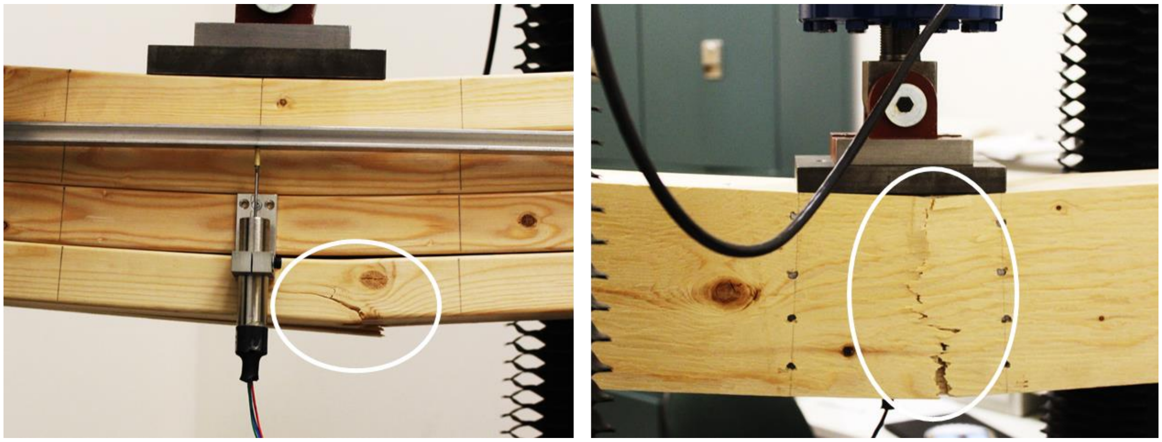

Figure 14 Failure of specimens in NLT bending shear test

3.1.3 Full size NLT wall test

The test results of full size NLT are presented in Section 3.2.2, together with the results of post laminated LVL walls.

3.2 Post laminated LVL

The average moisture content of post laminated LVL specimens was 8.1% (CV 2%). The average specific gravity was 0.517 (CV 4%).

3.2.1 Block shear and bending shear tests

The test results for block shear test and bending shear test are shown in Table 6. The average shear strength was 6.35 MPa for block shear test, and 4.84 MPa for bending shear test. The block shear group had a higher coefficient of variation, 27% compared to 9% of the bending shear group. All specimens in the bending shear test failed in horizontal shear, as shown in Figure 15.

Table 6 Block shear and bending shear test results

	Block shear test		Bending shear test	
	Peak load (kN)	Shear strength (MPa)	Peak load (kN)	Shear strength (MPa)
Maximum	21.8	11.40	45.3	5.65
Minimum	6.8	3.55	30.0	3.74
Average	12.1	6.35	38.9	4.84
Stdev	3.3	1.74	3.4	0.42
CV	27%	27%	9%	9%

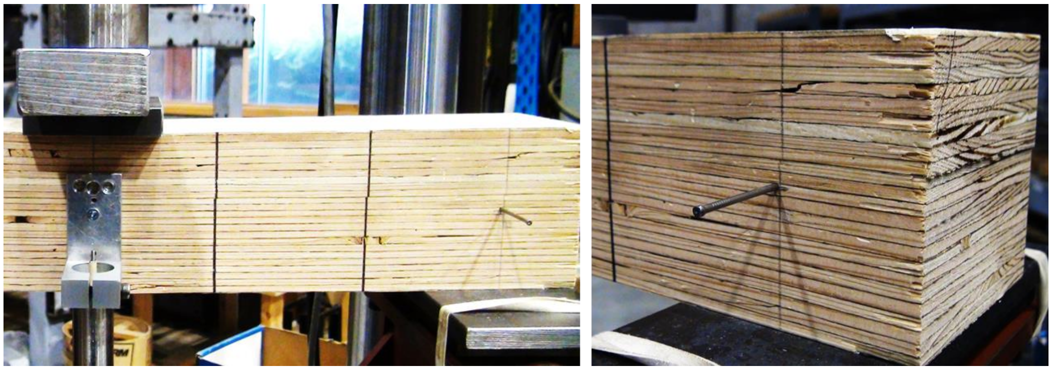

Figure 15 Horizontal shear failure in bending shear test

The cumulative probability plots for the two groups are shown in Figure 16, with another set of data obtained from TEAM database. This additional data was from a bending shear test on the same product (bending shear #1 in the figure). The nominal dimensions of the specimens were: 2134 mm long, 241 mm wide, and 267 mm deep. The span was 1867 mm with a span/depth ratio of 7:1. The load applied at two points in the center with 475 mm in between.

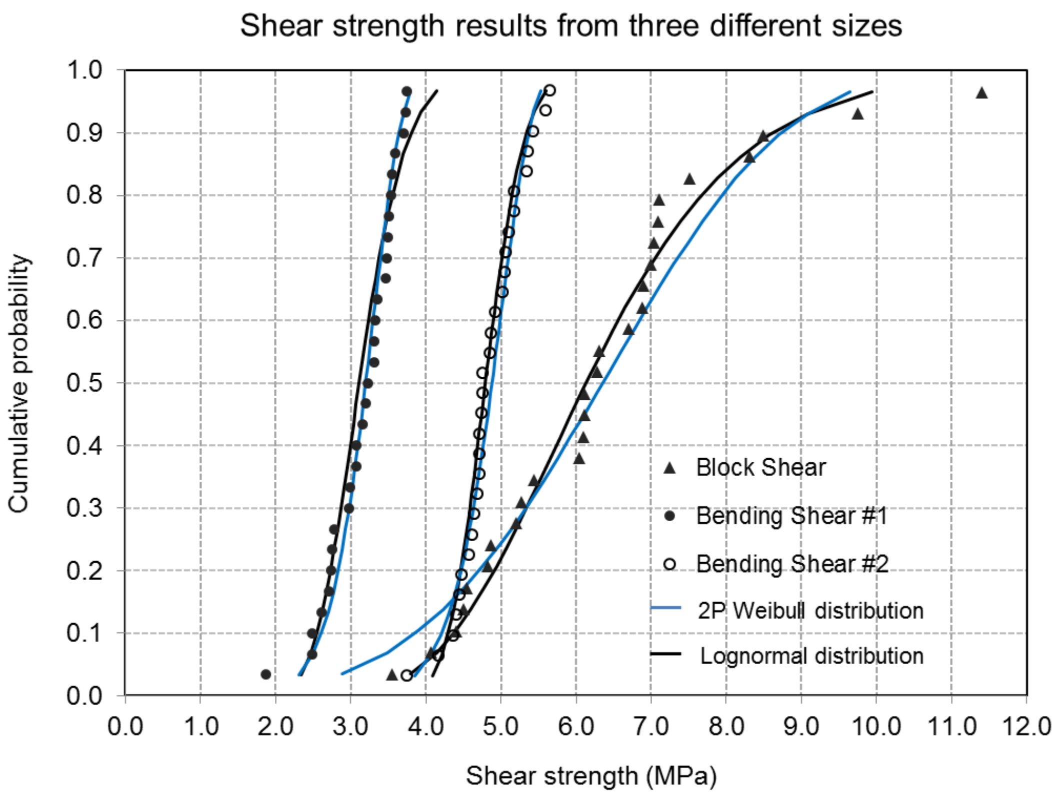

Figure 16 Cumulative probability plots for shear strength test results

Lognormal distribution (black) and 2P Weibull distribution (blue) were fitted to every data set. The distribution parameters are shown in Table 7. For the block shear test data, lognormal distribution was much better. For the bending shear test data, 2P Weibull distribution was slightly better, especially at the tails. The two sets of bending shear data had similar shape (similar CV as well) and they differed mainly on the location in the plot.

Table 7 Distribution fitting parameters for shear strength test data

Data set	Block shear		Bending shear #1		Bending shear #2	
Distribution	Lognormal	2P Weibull	Lognormal	2P Weibull	Lognormal	2P Weibull
Mean/ Scale	1.81	7.00	1.14	3.33	1.57	5.02
Stdev/ Shape	0.27	3.78	0.16	9.22	0.09	12.77

3.2.2 Full size post laminated LVL wall test

The full size wall test results are shown in Table 8. The load-displacement relationship of the monotonic test is shown in Figure 17. The data of two light wood frame shear walls was obtained from TEAM database for comparison (LFW-01 and 02 in Table 8). It is to be noted that post laminated LVL walls (LVL-01 and 02 in Table 8) had only about half the size of the rest walls (see Tables 2 and 3). Therefore one can also examine the capacity with respective to the shear wall width to gain a more direct comparison between LVL walls and other walls.

Table 8 Full size wall test results

Wall	Sheathing	Loading protocol	Peak Load (kN)	Displacement at Peak load (mm)	Failure mode
LVL-01	N/A	Monotonic	35.4	42.8	Holdowns
LVL-02	N/A	Monotonic	36.0	41.0	Holdowns
NLT-01	N/A	Monotonic	20.8*	166.5*	Load did not decrease
NLT-02	Plywood	Monotonic	40.1	75.0	Connection with sheathing
NLT-03	Plywood	CUREE	32.9	80.3	Connection with sheathing
LFW-01	Plywood	Monotonic	24.5	72.0	Connection with sheathing
LFW-02	Plywood	CUREE	26.8	58.9	Connection with sheathing

Note: LFW- light wood frame wall, 2×4 Douglas fir, width 2.4 m, length 2.4 m
*: since the load did not decrease, these were the values when the test was stopped

Post laminated LVL walls had high strength and high stiffness, with a small variation between the two replicates. The shear stress was low, estimated to be 0.34 MPa under a peak load of 35-36 kN. The wall behaved as a rigid plate with little internal deformation. The diagonal transducer recorded a deformation of 0.3 mm at peak load in one wall and 0.1 mm in the other, compared to the original diagonal length of 2750 mm. The displacement of the wall mainly came from the holdown under high uplifting force. The holdown at the near end deformed and the nails were being pulled out of the wood, as shown in Figure 18. It was the nail pulling out that caused the drop from peak load. No visible failure was observed in the holdown at the far end or in the angle bracket. Since the performance of the wall was mainly determined by the behavior of holdowns, no reverse-cyclic loading was conducted.

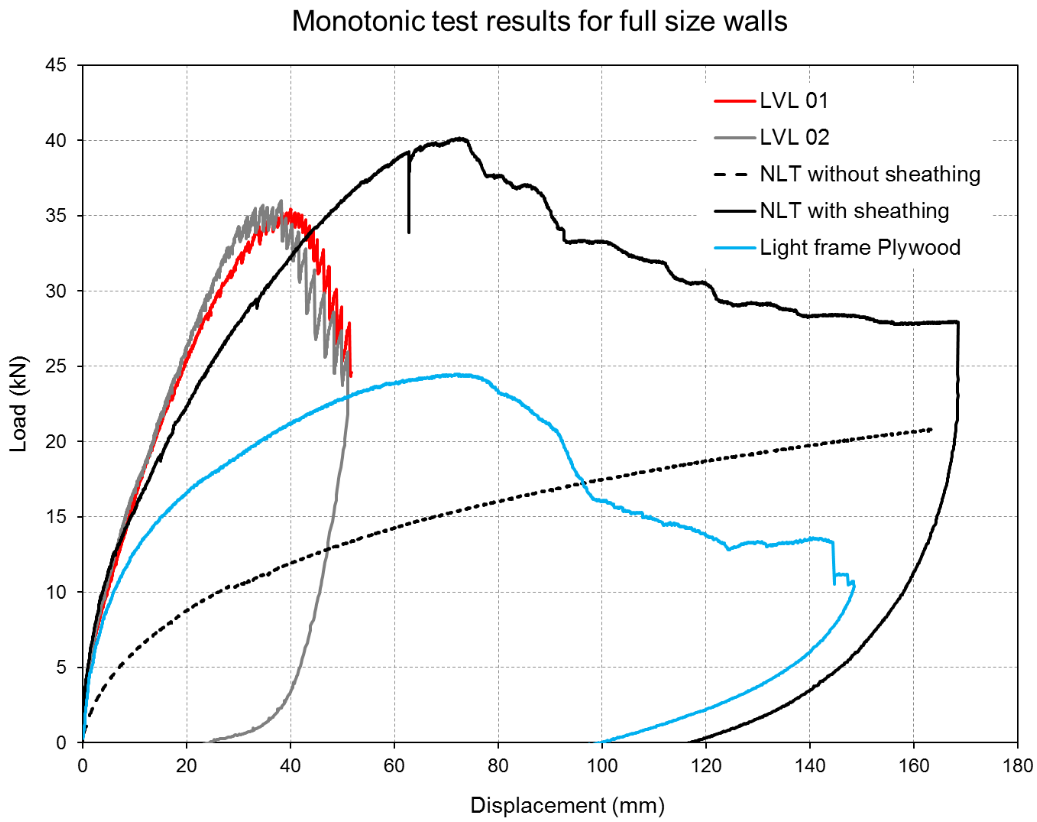

Figure 17 Monotonic test for full size walls

Figure 18 Failure mode of post laminated LVL wall

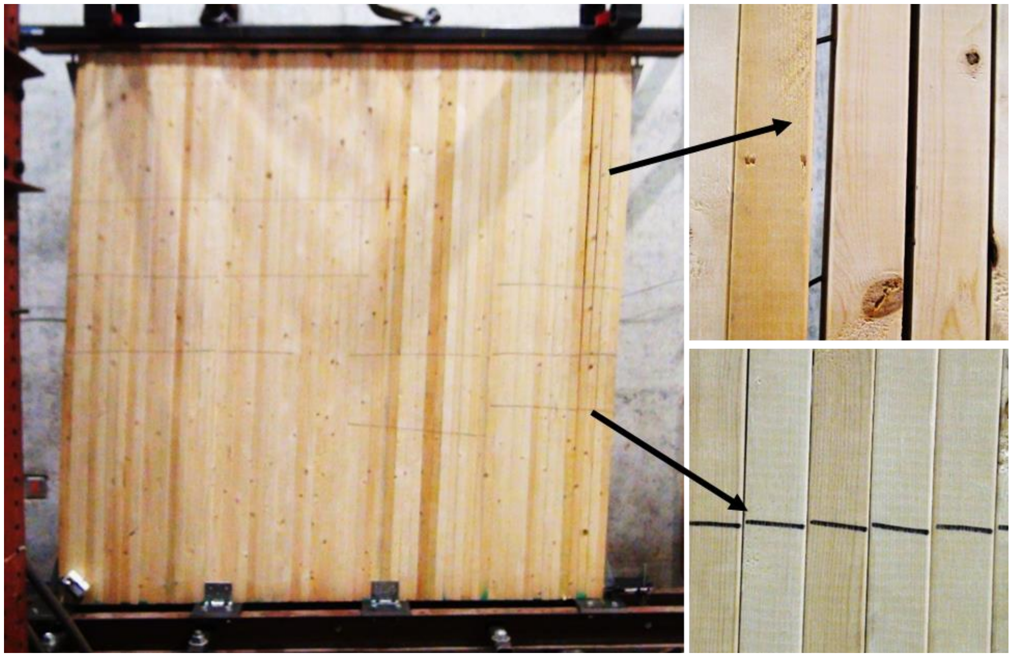

Figure 19 Failure of NLT wall without sheathing

The NLT wall without sheathing (NLT-01) had the lowest load-carrying capacity and the lowest stiffness, although the load did not decrease within the tested displacement. The lateral load applied was resisted by the nails between adjacent pieces of lumber. At the far end upper corner, some nails were pulled out, partly as a result of the lumber buckling under compression; the shear shifting of adjacent lumber elements was observed in other parts of the specimen, as shown in Figure 19.

Adding sheathing to the NLT wall significantly increased its strength and stiffness, as suggested by the previous bending shear test. Under monotonic loading, the NLT wall with sheathing had a much higher peak load than the light wood frame wall; and the two walls reached the peak load at similar displacements. The failure in the NLT wall with sheathing occurred at the connection between the lumber and sheathing, as commonly found in the light wood frame walls. Depending on the location in the panel, nail withdrawal, nail head pull through, and nail breakage occurred, as shown in Figure 20.

The cyclic test results are shown in Figures 21 and 22. Two monotonic test specimens are also included in Figure 22 for comparison. The NLT wall with sheathing still had higher load and stiffness than the light wood frame wall, although the difference was reduced. The NLT wall had better ductility, especially in the reverse cyclic tests. The area under the backbone curve was 5086 kN·mm for the NLT wall, about 30% higher than that of light wood frame wall, 3907 kN·mm.

Figure 20 Failure of NLT walls with sheathing

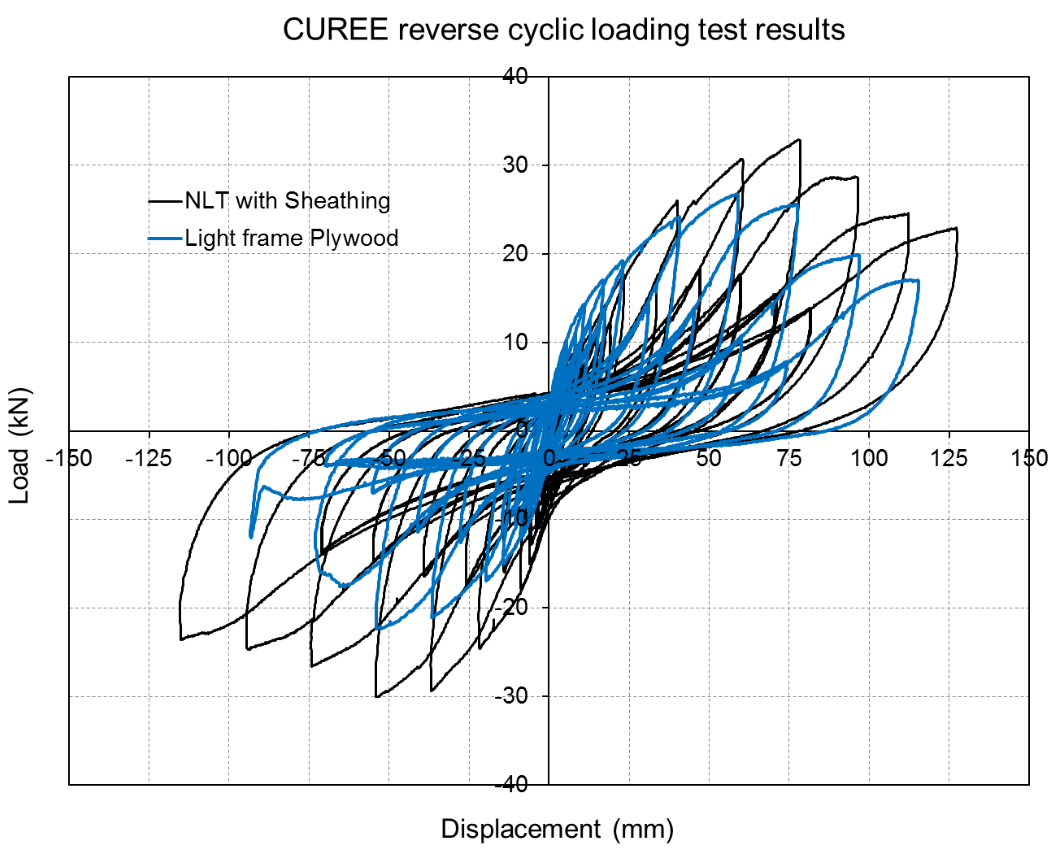

Figure 21 CUREE reverse cyclic loading test results

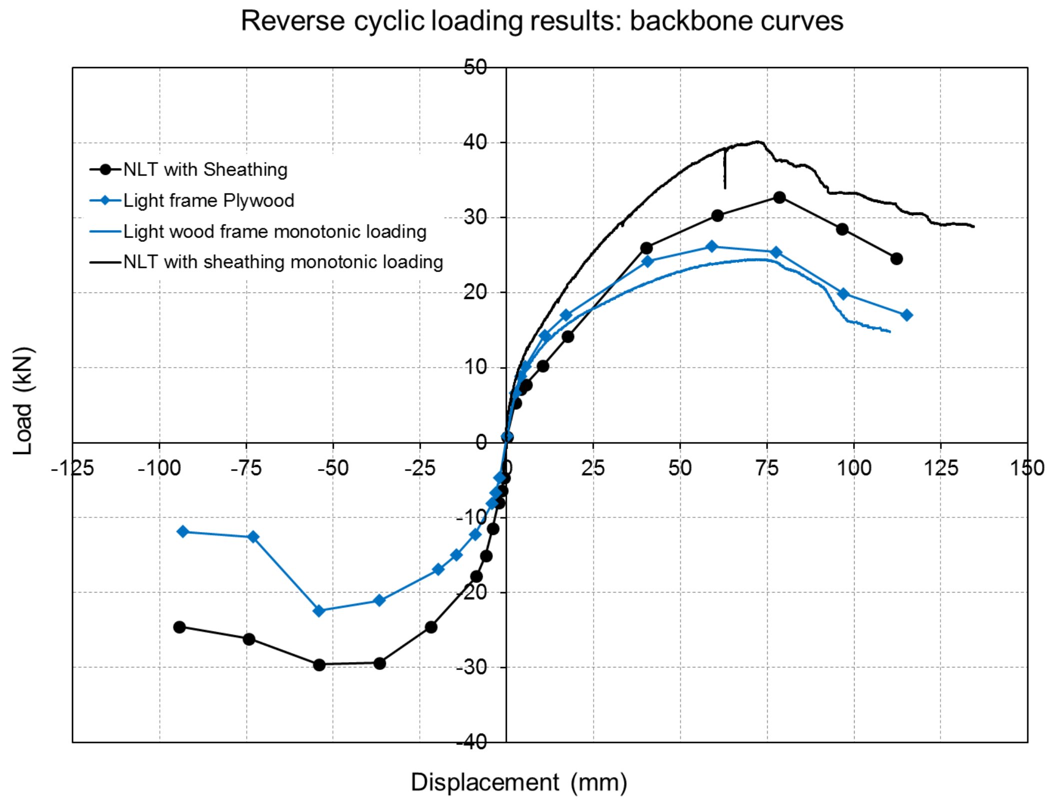

Figure 22 Reverse cyclic loading backbone curves

3.3 Further discussions

3.3.1 Application and design of NLT shear wall

The manufacturing of NLT shear wall does not require sophisticated equipment or highly skilled labor. Depending on the size and demand, it could be prefabricated in a factory or simply assembled on-site. The cost of NLT is lower than most massive timber products, and the design of NLT is well recognized in the building code. The thickness of NLT wall ranges from 89 mm to 450 mm by using dimensional lumber. Finger joint connection can be used to make longer elements. Alternatively the use of butt joint elements can also be tried although the consideration of uplift forces must be verified. The width and length thus will be mainly determined by the equipment, working space, and transportation.

Compared to light wood frame shear wall, NLT shear wall has higher lateral resistance, higher stiffness, better seismic performance, and much higher vertical load bearing capacity. Above all, since NLT is a massive timber product, its performance under fire is different from a light wood frame wall. The burning of wood on the surface generates a layer of charring protecting the wood below. Thus NLT shear walls may be used to increase the building safety under fire by replacing light wood frame walls at critical locations of a building. A well design NLT wall can also be exposed or be formed into curved shape, creating unique aesthetic effect.

Compared to CLT, NLT shear wall has higher vertical load bearing capacity and stiffness, although its lateral resistance appears to be lower even with sheathing. The NLT shear wall has an internal energy dissipating mechanics which CLT lacks: between lumber elements and between lumber and sheathing. This energy dissipating capacity may be important in some applications, since the demand on the connectors, as well as the potential damage to adjacent structural elements is significantly reduced.

The design of NLT lateral resistance can be divided into two parts: the lateral resistance provided by the NLT elements alone, and the resistance provided by the sheathing. The latter part is similar to that of a traditional light wood frame wall, and the number of nails, nail spacing could be adjusted according to the demand. The lateral resistance capacity of NLT elements may be calculated based on the test results of single nail connections, and the nailing pattern used. To ignore its contribution is not recommended since that will dramatically reduce the competitiveness of this product. When the NLT wall with sheathing reached the peak load in this test, the lateral load resistance provided by the NLT elements was estimated to be 33% of the total on average (38% in the monotonic loading and 27% in the cyclic loading).

3.3.2 Application and design of post laminated LVL shear wall

Post laminated LVL has a higher compressive strength and stiffness than CLT. The compressive strength parallel to grain is 35.2 MPa and the Modulus of Elasticity is 13.8 GPa (Brisco 2018). The thickness is up to 292 mm (11.5 in), close to a common 9 layer CLT. Its width is up to 1.2 m (48 in), and its length is up to 18 m (60 ft).

Since the design of CLT only considers the longitudinal layers under compression, post laminated LVL is more suitable to bear high vertical load, especially in taller timber buildings. The post laminated shear wall behaves as a rigid plate under lateral loading, which is similar to CLT. The displacement of the wall mainly comes from the deformation at connections.

One critical design criteria for post laminated LVL walls is the shear strength, which may be the governing factor for a large, tall wall plate. The height/width ratio of the wall tends to be higher than that of CLT. The size effect of shear stress in post laminated LVL walls may be obtained from the test results based on Weibull Weakest Link principles. The current connection techniques for CLT could be adopted in the application of post laminated LVL walls. The connection design needs to pay particular attention to the presence of tension perpendicular to grain stresses, as such certain reinforcements may be considered, for example, using self-tapping wood screws.

Post laminated LVL walls have an elegant surface created by thin layers of veneers. And the surface is wear and abrasion resistant due to its veneer alignment. Its fire resistance is equivalent to that of CLT, with an estimated charring rate of 0.68 mm/min (Brisco 2018).

4 CONCLUSIONS

The feasibility and performance of massive timber shear walls based on NLT and post laminated LVL were investigated in this project.

The NLT wall without sheathing had the lowest load-carrying capacity and lowest stiffness. Adding sheathing to the NLT wall significantly increased its strength and stiffness. The failure in the NLT wall with sheathing was similar to that found in the light wood frame walls: at the connections between the sheathing and lumber, in the forms of nail withdrawal, nail head pull through, and nail breakage. The NLT wall with sheathing had a peak load up to 60% higher than the light wood frame wall of the same size. The internal energy dissipating capacity is one advantage of NLT shear walls, which will significantly reduce the damage to adjacent structures and connections. As a massive timber product, NLT shear walls are able to provide good fire safety even when exposed.

The post laminated LVL walls behaved as a rigid plate under lateral loading, with little internal deformation. The failure occurred at the holdowns: the metal deformed and the nails were pulled out of the wood. An equation was developed from test data to calculate the size effect of its shear strength.

Both products have efficient vertical load bearing mechanism by arranging all elements in the vertical direction. They may serve as alternative to light wood frame walls or CLT walls. Some guidelines for the application and design of NLT shear walls and post laminated LVL shear walls were proposed.

5 ACKNOWLEDGEMENTS

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Appendix A Specifications of specimens in NLT test

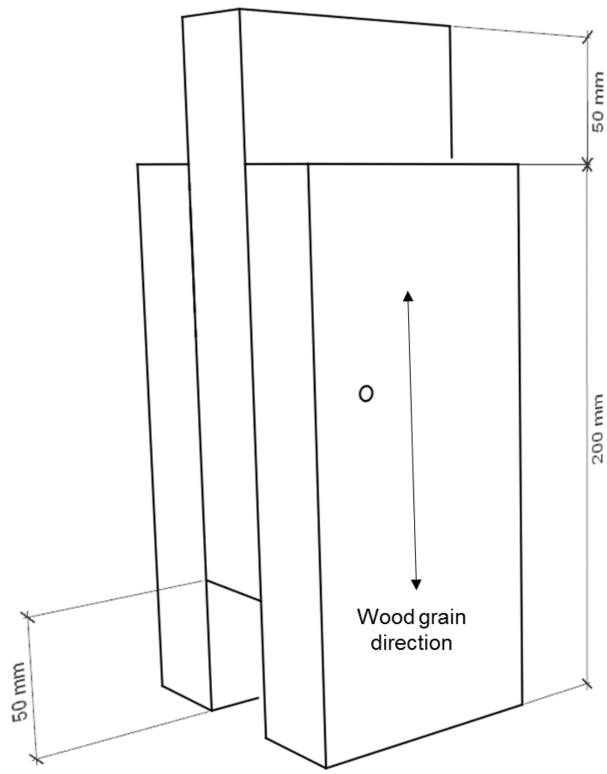

Figure A- 1 Nail connection test specimen with nails parallel to wood grain

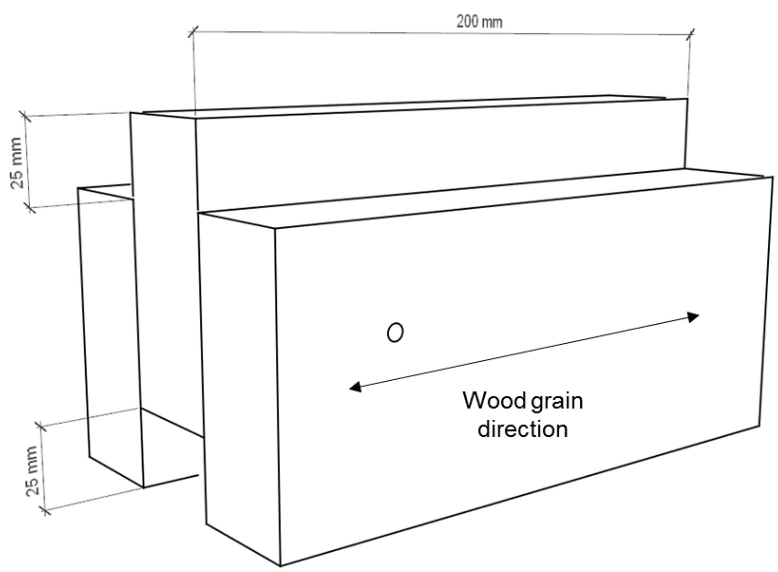

Figure A- 2 Nail connection test specimen with nails perpendicular to wood grain

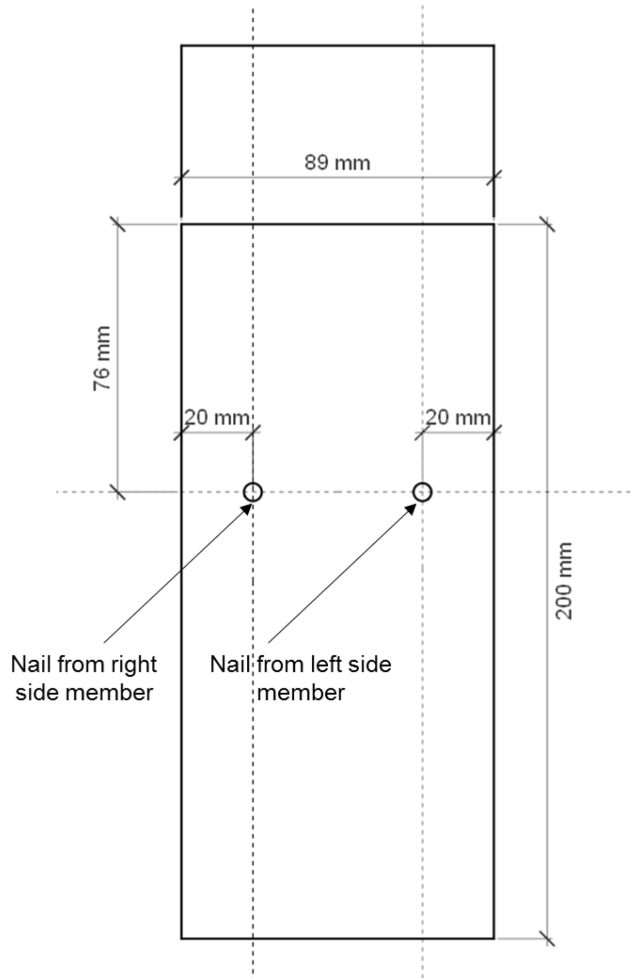

Figure A- 3 Nail locations for specimens with nails parallel to wood grain

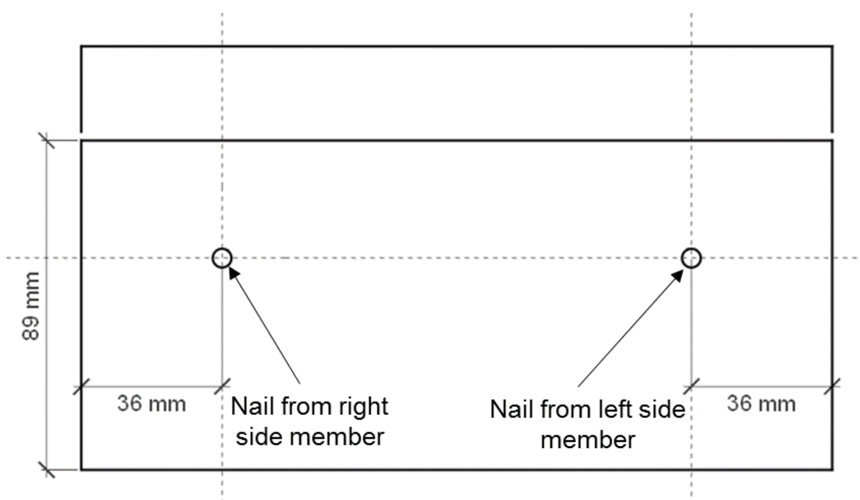

Figure A- 4 Nail locations for specimens with nails perpendicular to wood grain

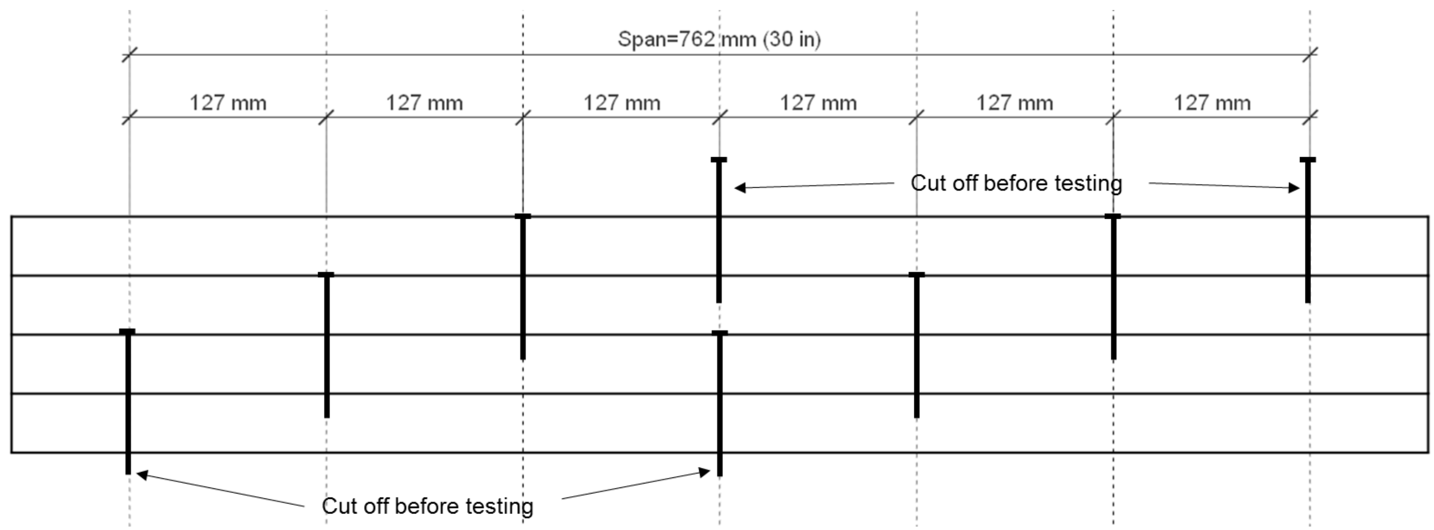

Figure A- 5 NLT bending-shear test specimen: nail locations front view

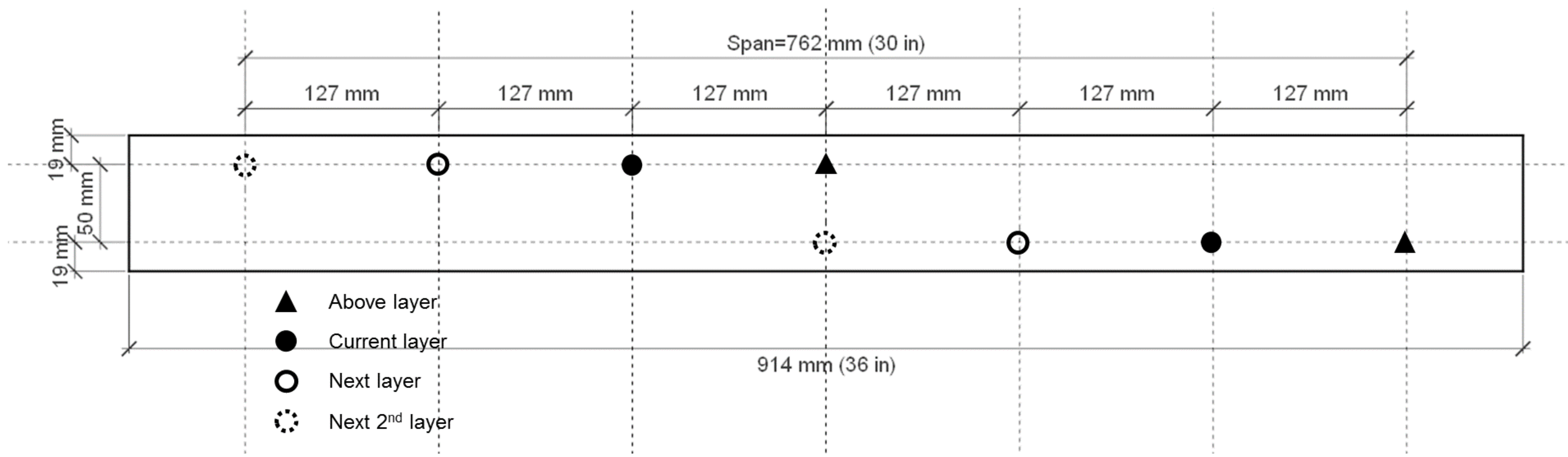

Figure A- 6 NLT bending-shear test specimen: nail locations top view

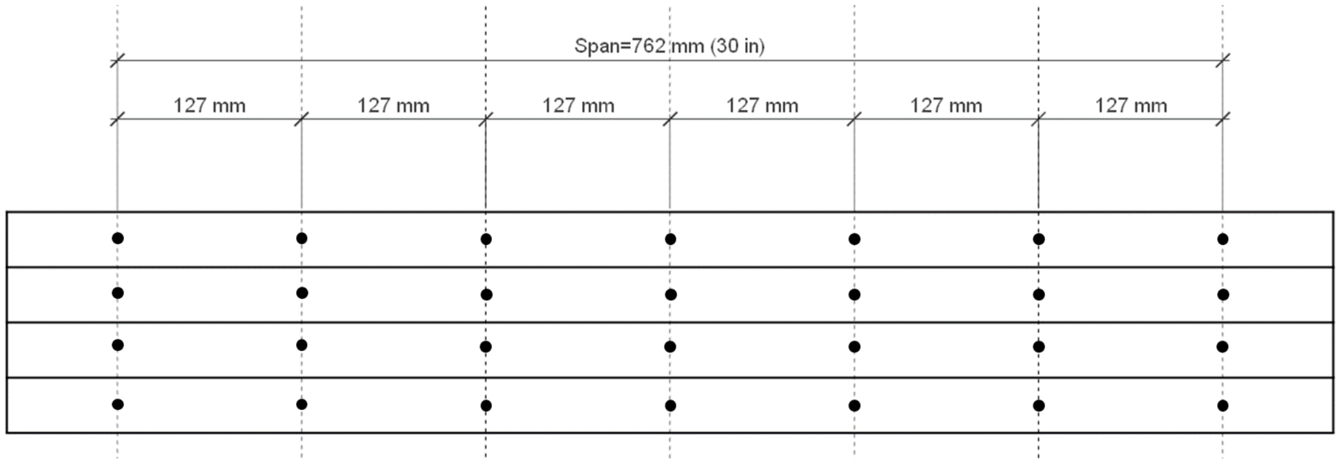

Figure A- 7 NLT bending-shear test specimen: nail locations for plywood sheathing

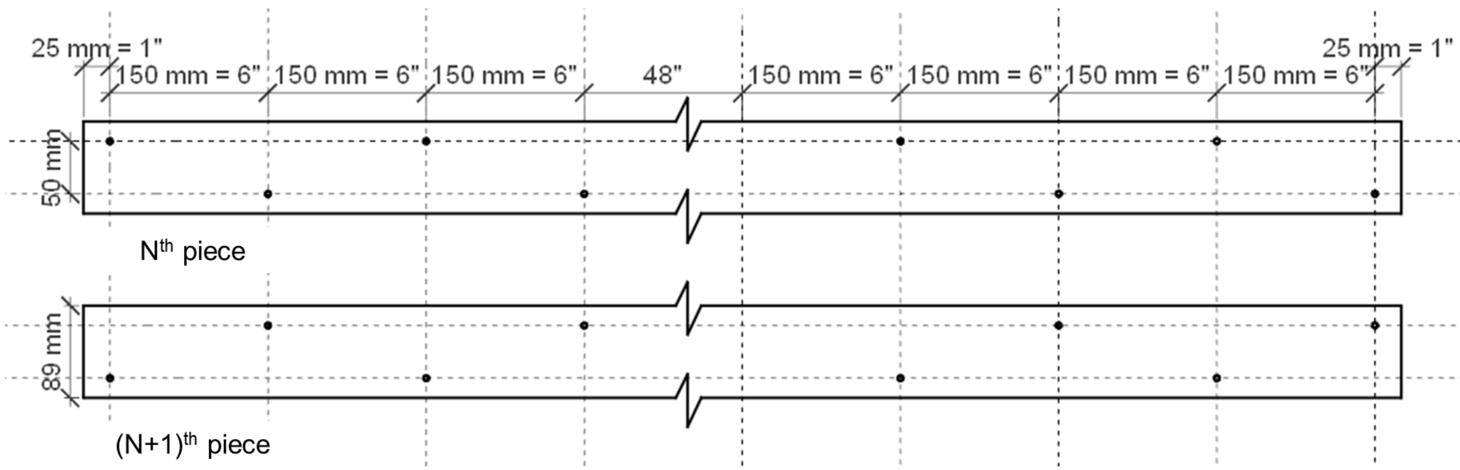

Figure A- 8 NLT wall specimen nailing pattern

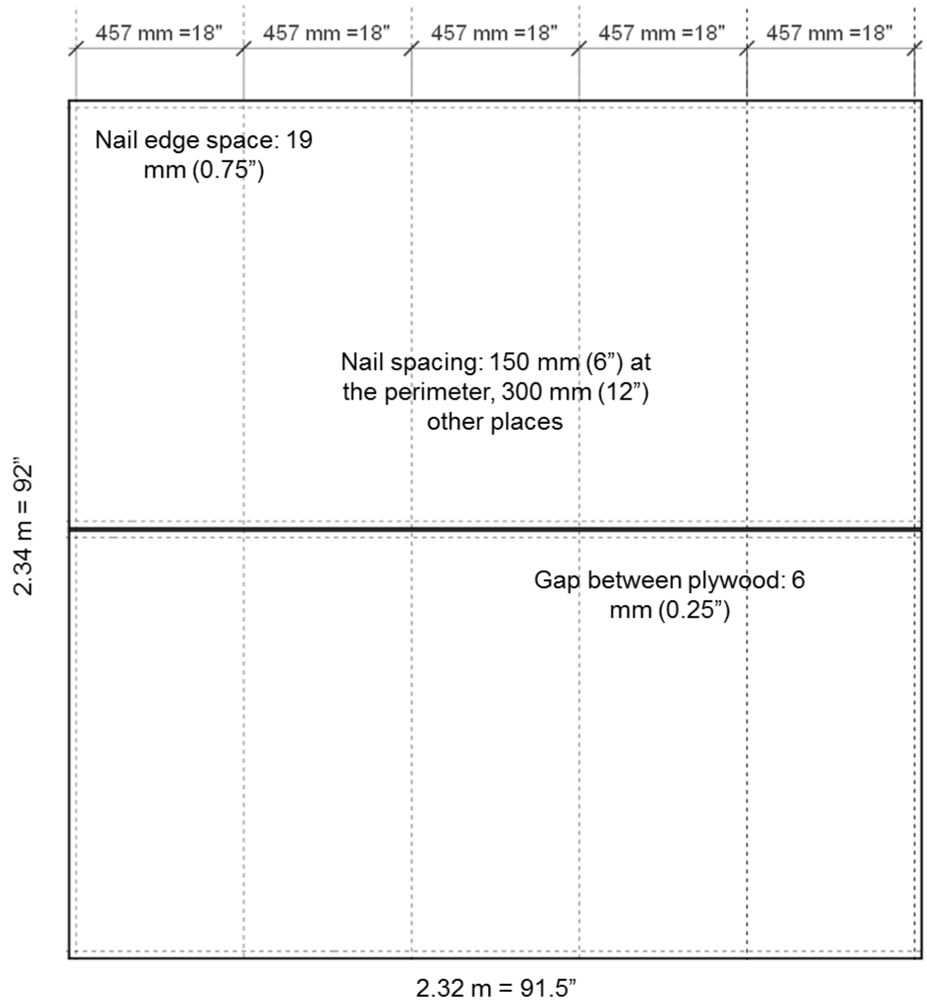

Figure A- 9 Nailing pattern for plywood sheathing (dotted lines)

Appendix B CUREE basic loading protocol

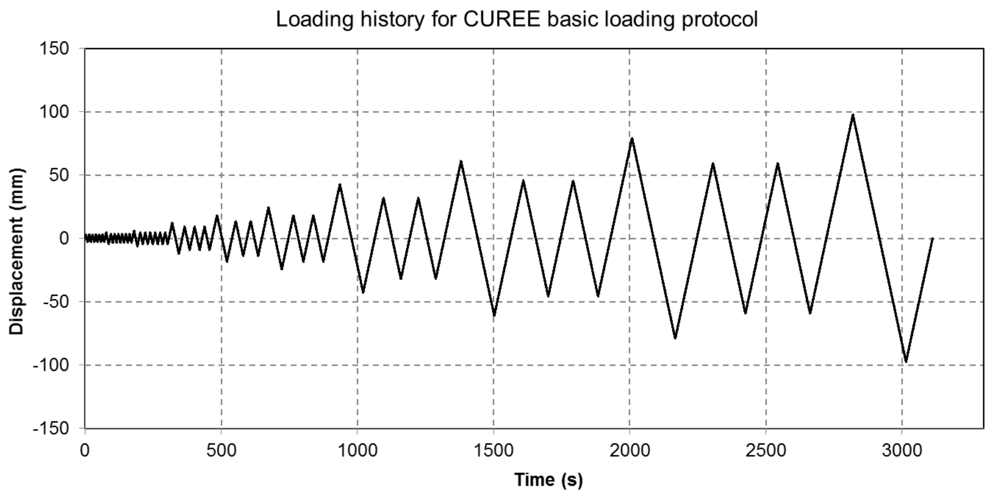

Figure B- 1 Loading history for CUREE basic loading protocol

Table B- 1 Amplitudes of CUREE basic loading protocol

Step	Number of cycles		Amplitude (mm)
1	Equal	6	3.0
2	Primary	1	4.5
	Secondary	6	3.4
3	Primary	1	6.0
	Secondary	6	4.5
4	Primary	1	12.0
	Secondary	3	9.0
5	Primary	1	18.0
	Secondary	3	13.5
6	Primary	1	24.0
	Secondary	2	18.0
7	Primary	1	42.0
	Secondary	2	31.5
8	Primary	1	60.0
	Secondary	2	45.0
9	Primary	1	78.0
	Secondary	2	58.5
10	Primary	1	96.0
	Secondary	2	72.0

THE END